Determining the Pressure of Tight Pants on Human Body by Numerical Simulation Method

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Abstract

This paper focuses on the determination of wearing pants-induced pressure on young female legs by using a numerical simulation method. A 3D biomechanical model for simulating the pressure magnitude and distribution is constructed based on the actual geometry of a female leg obtained from 3D reconstruction of computerized tomography (CT) scan images. The biomechanical solid leg model consists of three main components: skin, bones, and soft tissues. A shell model is also built for the trouser leg. The mechanical properties of bones are assumed to be a rigid material, while skin and soft tissues are considered as homogeneous linear elastic materials. Material properties of trouser fabrics are experimentally determined through tensile tests. The commercial finite element program ABAQUS is employed to simulate the pressure distributions and biomechanical responses induced by wearing pants at three typical cross-sections of legs. In addition, experiments for measurement of pressure distribution are further carried out. A careful comparison between simulation and experimental results shows a good qualitative and quantitative agreement, which suggests that the proposed biomechanical model can be used to predict, analyze, and determine pressure of tight-fit cloth on human body. The present study thus provides a reliable and efficient way for clothing design that satisfy the comfort conditions in use.

Keywords: Tight-Fit Cloth Pressure, Cloth Simulator, Numerical Simulation, Skin Pressure

1. Introduction

The fit and size of clothes are of important factors in determining the clothing comfort, which is essential in the research area of ergonomics. In the case of wearing tight-fit clothes, the fabric is usually stretched to adapt individual Fig.s, in turn, it tends to shrink and exerts pressure or compression on the wearer's body surface because of its high elasticity. A high pressure induced by tight-fit clothes wearing can cause irritation, alter the excretion of the skin, and affect the ability of blood circulation in the human body. With increasing demand for garment comfort, it is therefore neccessary to investigate the pressure distribution and comfortable pressure range of tight-fit garments.

Recent advances in electronic pressure sensors have enabled the garment–human interface pressures to be measured [1,2], however, the pressure measurements are difficult and time-consuming tasks, and often influenced by several factors, such as the selection of the pressure sensors, the positions to apply the sensor, and the methods of measurement [3]. To alleviate this issue, the use of numerical methods could facilitate to predict pressure distribution in the early stages of the design process. Several studies have been conducted to determine the pressure of tight-fit clothes and examine the clothing comfort using numerical methods. For instance, Cai *et al.* [4] have applied finite element method (FEM) to simulate the pressure of wearing bra on the female body. This study has used a 3D simulation model, in which the human body geometry is constructed from 3D body scan data and all parts of the body are assummed as homogeneous linear elastic materials. The simulated results have provided theory for calculating the mechanical effects of clothing on the human body. Zhang *et al.* [5, 6] have constructed a 3D finite element model of a female body by using a commercially available virtual human model that can describe the contact between the human body and clothing. The virtual mannequin is assumed to have a hard surface that is undeformed during wear process, therefore, the mechanical interactions between the fabric and the inner soft tissue layers are not taken into acount. However, it is surprising that there are few studies examining the tight pants-induced pressure on human legs, despite of its important role in maintaining the foot comfort.

In this study, we construct 3D biomechanical model that simulates the shapes, sizes, and structures of a Vietnamese young female leg. The model includes

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three main components: skin, soft tissues, and bones. The finite element program Abaqus is employed to calculate pressure and deformation distributions of the wearing tight pants on the leg. Experiments for measurement of pressure distribution are further carried out. A comparison between simulation and experimental results is drawn and discussed.

2. Methodology

2.1 Modelling structures of human body and clothing

In this study, the geometry of the FE leg model is obtained from 3D reconstruction of CT scan images from the right leg of a healthy and normal female subject of age 20, height 160 cm, weight 52 kg, and BMI index 20,31. According to standard TCVN 5782-2009 [9], the basic size parameters are accordance with size 158B. The CT scan images are taken in the neutral unloaded position to attain the anatomic structures of leg cross-sections. The right leg structure used in the present study is modeled with three main parts consisting of skin with thickness of 1,5 mm [6], soft tissues, and bones. For simplification, the layers of soft tissues, which includes muscles, tendons, blood vessels, and nerves, are assumed to be homogeneous medium. Boundary surfaces of skin, soft tissues, and bone are modeled as solid body structures using SolidWorks software, as shown in Fig. 1 [10].

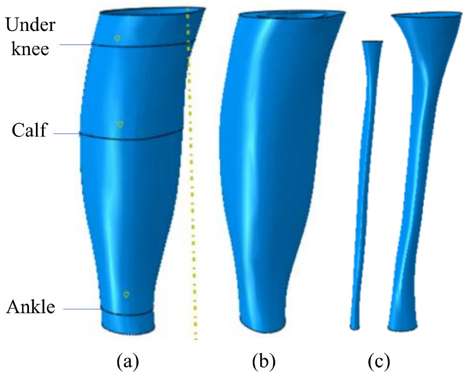

Fig. 1. 3D modelling structure of human legs constructed from CT scan data: (a) Skin, (b) soft tissue, and (c) bone models.

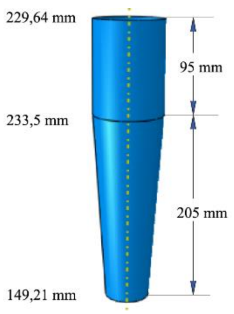

Fig. 2. 3D model of a trouser leg.

Fig. 2 shows a shell model of the trouser leg with round tube shape. The tube length is set to be 300 mm. The sample circumferences l with different elongation are calculated on the basis of Eq. (1).

$$l = \frac{l_0}{1+\varepsilon}, \quad (1)$$

Where l is sample circumferences, l_0 is original sample circumference, and ε is the horizontal elongation of the fabric. In the clothing design, the stretch of the fabric typically ranges from 10% to 60% [1]. In this study, the stretch of the fabric is thus selected to be 40% for the determination of wearing trousers-induced presure on human legs. Calculated results for the size of trouser leg with respect to the horizontal elongation of fabric are summarized in Table 1.

Table 1. Size of trouser leg with 40% elongation of the fabric

Measure position	Ankle size	Calf size	Knee size
Human body size	208,9	326,9	321,5
Trouser leg size	149,21	233,5	229,64

2.2 Material properties

In this study, bones are considered as a rigid material since it is subjected almost no deformation under pressure of clothing on skin surface. Skin and soft tissue are considered as homogeneous linear elastic materials. Machenical properties of skin and soft tissues, including elastic modulus (Young's modulus), Poisson's coefficient, and specific weight, are listed in Table 2.

Table *2.* Mechanical properties of human body [6, 8]

Components	Elastic modulus (Mpa)	Poisson's coefficient (v)	Specific weight (ton/mm^3)
Skin	0,15	0,46	1,06E-09
Soft tissue	0,06	0,48	0,937E-09
Bone	7300	0,3	1.58E-06

The knitted fabric used in this study is defined as a homogeneous linear elastic material. The correlation between stress σ and strain ε is described by Hooke's law, as:

$$\sigma_{ij} = C_{ijkl}.\varepsilon_{kl} \qquad (i, j, k, l = 1, 2, 3), \qquad (2)$$

where C_{ijkl} is tensor of elastic constants. The material properties of fabric is determined by an experimental method at textile materials laboratory of School of Textile - Leather and Fashion, Hanoi University of Science and Technology. The elastic moduli of fabric in the longitudinal and transverse directions are determined in the tensile strength test according to

ASTM D-4964-96 standard. During the tensile tests, the relation between pressure and elongation magnitudes of the samples keeps linearly until the elongation reaches about 80% of the samples. The determined parameters of fabric samples used in the study are presented in Table 3, in which W denotes specific weight, E_1 and E_2 are elastic modulus, v is Poisson's coefficient, G_{12} is elastic slider modulus (Shear modulus), and T is thickness of fabric sample.

Table 3. Mechanical properties of fabric

W (tonne/mm^3)	E_1 (N/mm^2)	E_2 (N/mm^2)	V	G_{12} (N/mm^2)	T (mm)
4,03E-10	0,3986	0.4122	0,325	0,376	0,39

2.3 Simulation model

The FE leg model used in this study contains 684676 elements of R3D4 with averaged size of 3 mm. For investigation of pressure distribution and deformation, three typical cross sections at ankle, calf, and under knee are mainly considered. In the skin model (Fig. 1), these cross-sections are divided into 72 equal parts, in which each part corresponds to an arc with angle of 5 degrees [7]. Fig. 3 illustrates the meshing of ankle cross-section by using SolidWorks software [10]. The relative coordinates in the x and y directions of 72 points are determined by using Autocad software. With the rigid body assumption, all nodes on the meshed surfaces of bones are fixed.

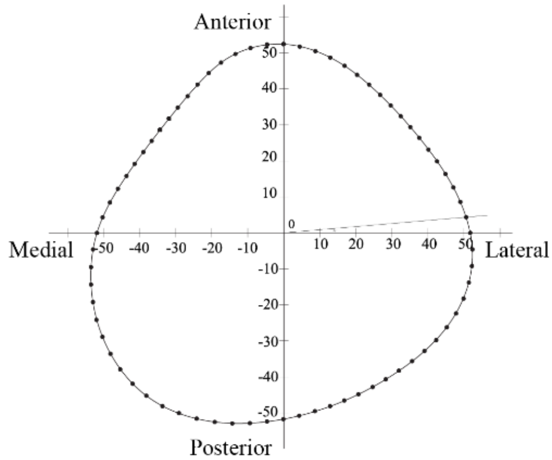

Fig. 3. Shape of the cross-section calf.

The FE shell model of trouser leg uses S4R elements, which are four-node conventional shell elements with reduced integration. The averaged size of element is about 3 mm (Fig. 4b). The top edge of the trouser leg is constrained and allowed to move only in the vertical direction from the ankle upwards within a range of 320 mm in 10 seconds [8] (Fig. 4a). The other sides of the trouser leg are unconstrained.

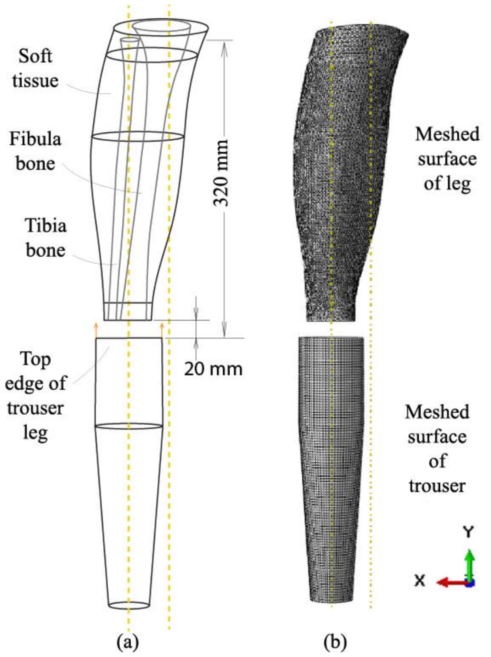

Fig. 4. (a) boundary condition of bone and trouser leg in finite element model, (b) meshed model of leg and trouser leg.

3. Results and discussion

3.1 Pressure distribution on cross sections

The pressures of fabric on the skin surface at three cross-sections of under knee, calf, and ankle are calculated and achieve the mean magnitudes of 20.93 mmHg, 21.35 mmHg, and 24.37 mmHg, respectively. This result show that the pressures at three considering cross-sections of the legs are different despite of the same horizontal elongation of the fabric.

The mean pressure is highest at the ankle position and reduced at cross-sectional positions with larger perimeters. Fig. 5(a), (c), and (e) shows the pressure distribution on the three cross sections. The pressure at 72 positions on the under knee cross-section is evenly distributed, as shown in Fig. 5(a). On the under knee cross-section, pressure has the maximum value of 34.28 mmHg at the position with angle of 225° and the minimum of 13.59 mmHg at a 110° angle. On the calf cross section, the pressure varies significantly, where the highest pressure is concentrated at the front, outside of the leg at 90° and 330° angles (Fig. 5(c)). At the ankle position, the pressure tends to increase gradually in the range of [90°, 145°], while it changes insignificantly in the ranges of [155°, 235°] and [270°, 360°]. Based on these analyzed results, we find that the wearing trouser-induced pressure is concentrated in the area with small curvature on the same cross-section, such as the front and back sides of ankle, and outside and front side of calf.

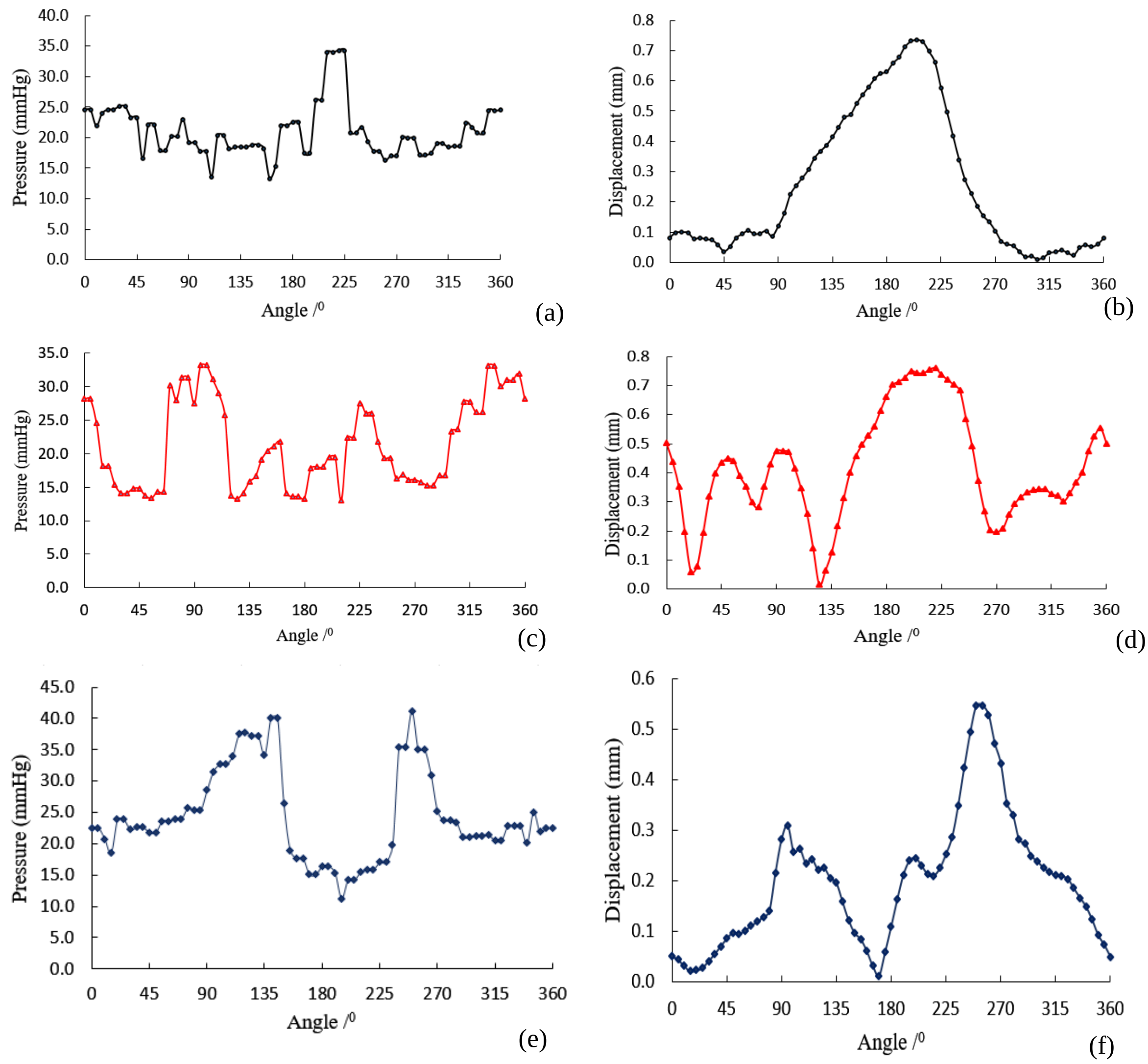

Fig. 5. (a) Pressure distribution on cross-section under knee; (b) Displacement of 72 points on cross-section under knee; (c) Pressure distribution on cross-section of calf; (d) Displacement of 72 points on cross-section of calf; (e) Pressure distribution on cross-section of ankle; (f) Displacement of 72 points on cross-section of ankle.

3.2 Deformation on cross section

The elasticity of stretched fabric causes pressure on the skin surface, and thereby, give rise to a deformation of the skin surface and the soft tissue layers. In this study, displacements of 72 points on the cross-sections are determined, as shown in Fig. 3. The radial displacement is caculated based on the evaluated magnitudes of displacements in the *x*, *y*, and *z* directions. Fig.s 5 (b), (d), and (f) plot the radical displacement curves of 72 points on the three cross-sections of under knee, calf, and ankle, respectively. The displacement curves show that all the nodes on the three cross-sections change due to the pressure of the fabric on the skin surface. Although the ankle area had highest pressure, its displacements is smaller than that at the calf and under knee. This suggests that the displacement value is disproportional to the pressure on the surface.

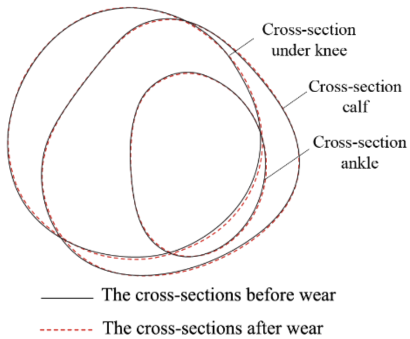

Fig. 6. Comparison of cross-section deformation between simulation and after deformation curve.

The areas behind the leg had the largest displacement from the 180° to 270° angle. The maximum radical displacements are calculated at the cross-section of under knee, calf, and ankle are 0.74 mm, 0.76 mm, and 0.55 mm, respectively.

Comparisons of deformation at the three cross-sections before and after wearing are shown in Fig. 6. At the ankle where the maximum average pressure is present, the deformation is smallest compared to that at the two other positions. After wearing, the perimeter of boundary curves increases 0.5% at the under knee, while it decreases 0.13% and 0.62% at the ankle and the calf, respectively. The bounday curvatures of the cross-sections are rounded at positions with small curved radius after wearing trousers. Therefore, under the pressure of tight-fit clothing, the surface curves have been reshaped.

3.3. Comparisons between the Simulated and the Measured Results

An experimental mesurement of presure distribution induced by tight-fit clothes is carried out by using a pressure measuring device [11], which composes of a FlexiForce sensor manufactured by Tekscan USA, an electric circuit, and a computer with built-in software to display the measured data. High sensitivity sensors are attached between the fabric and leg surface. The experiment is conducted by measuring pressure at 12 points on the right leg of the young female, which are at frontal, outer, rear, and inner points on the three cross-sections as considered in the above simulation. The tests are carried out in standing position, in which each position is measured five times. The mean values of five measurements are listed in Table 4.

Table 4. Value table according to simulation and experimental method

Measuring position	Result	Anterior	Medial	Posterior	Lateral
Ankle	The simulated	33.35	22.17	25.30	18.90
	The measured	23.75	17.52	22.00	15.00
	Error (%)	40.42	26.54	15.00	26.00
Calf	The simulated	26.27	21.22	16.11	20.00
	The measured	24.80	19.03	17.00	18.00
	Error (%)	5.93	11.51	5.25	11.11
Under knee	The simulated	23.12	19.34	17.04	18.24
	The measured	20.12	17.55	14.03	16.33
	Error (%)	14.91	10.20	21.47	11.69

A careful comparison between simulation and experimental results in table 4 and Fig. 7 shows that the change of pressure according to positions obtained from experiment has the same tendency with that from simulation. The magnitudes of pressure obtained from experiment are smaller than that from simulation. The largest difference between experimental and simulation results are observed at the ankle. The average error between the two methods is evaluated about 16.67%. Such a good qualitative and quantitative agreement suggests that the computational simulation can be applied in practice to quickly forecast and draw pressure distribution induced by tight-fit clothes, and thus is an efficient approach.

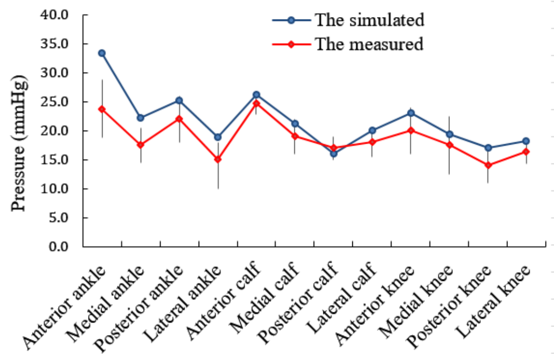

Fig. 7. Comparison chart of pressure value based on empirical test and calculating simulation.

4. Conclusion

In this study, we have successfully developed a 3D biomechanical simulation model to determine pressure of tight pants on the female legs. The obtained results show that the pressure distribute differently on the leg surface even with the same horizontal elongation of the fabric. The pressure of the trouser leg on the leg surface is induced by the elasticity of the stretched fabric, which can change the shape and size of the leg, and induce pressure on the inner layers of tissue.

The biomechanical model yields a good agreement with the experimental measurement, in which the errors between two approaches are in an allowable range. The proposed model provides a better understanding of biomechanical responses during the clothing wear process. This also provides an efficient way for the design of tight-fit clothing in several applications such as medical use, sports, and cosmetology orthopedics.

The actual interactions between clothing and the human body are more complex than our simulation model, because of the complexity of biological materials and human anatomy structure, non-linear geometry deformation of the trouser leg, different movement postures and different human body shapes.

The present model can be further developed to take into account these factors, however, more efforts are requried in the future works.

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